Monitoring Siltation

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Introduction

Part I of this document analyses the justification for spill monitoring. Part II describes a method for monitoring the environmental impact of sediment spill in or near water, such as when dredging or building. Part III discusses how permit conditions may be formulated to exploit the full environmental and societal benefit from this monitoring method. The target audience includes professionals involved in monitoring sediment pollution, issuing permits, or supervising that the permits are followed.

Part I: Justification

Monitored Parameters

Sediment spill may negatively affect the biota. Benthic filtering organisms are sensitive for sediment accumulation and elevated near-bed sediment concentrations. The graph below illustrates a measurement station with a SediMeter.

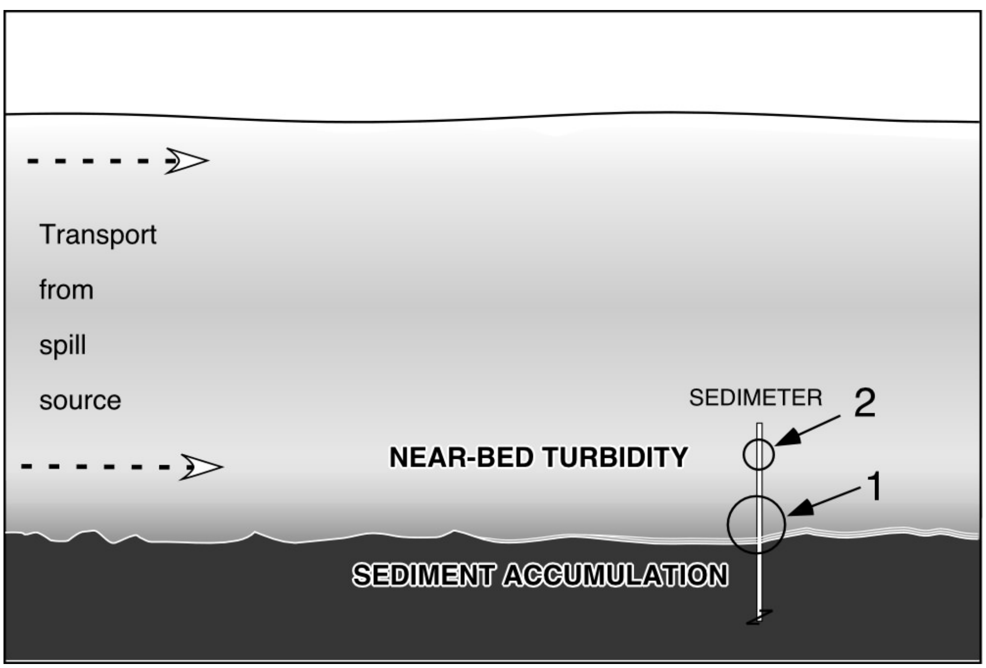


Figure 1. The environmental impact of the spill relates to the sediment accumulation, and the sediment concentration in the water. Much of the suspended sediment occurs close to the bottom, but some also appear at the surface where a bucket dredger spills its water on the way to the dredge. Sediment concentration is measured as turbidity, e.g. using an optical backscatter detector (OBS). The sedimeter (Erlingsson, 1991; Thomas & Ridd, 2004) consists of an array of overlapping OBS detectors arranged so that both the bottom level can be monitored (1), while a dedicated OBS measures near-bed turbidity (2). Together they are referred to as siltation. The sedimeter measures FTU (formazin turbidity units) in a manner similar to the ISO 7027 standard, the significant difference being that it measures 180° scatter rather than 90° scatter. To distinguish the units, the sedimeter FTU is called FBU, the ISO is called FNU (B = backscatter, N = nephelometric).

Why Monitoring

Building activities, dredging, and other construction activities in or near water may bring sediment into suspension. While in suspension, sediments can be transported by currents to sensitive biotopes. Eventually the suspended sediment will settle to the bottom. It may accumulate permanently, or get re-suspended at a later time. Coarser fractions may get transported further as bed load.

Most if not all bottom-dwelling organisms have a limited tolerance to these processes. To protect the environment the spill must therefore be limited. Monitoring is necessary in order to supervise the compliance with the permit.

In certain cases, sediment spill may cause sediment accumulation in navigation channels. New construction may also have negative side effects in the form of erosion, or scour, in neighboring areas. These negative effects for other stakeholders may not be fully known until long after the project is terminated. Long-term monitoring may then be necessary in order to quantify the side effects, either as a basis for determining appropriate monetary compensation to other stakeholders, or to determine the need for mitigating remedies.

Monitoring may be used as a quality tool in order to assure that the project has the intended benefit. In a recurring project, monitoring may be used to determine the timing of the next activity, e.g., the next dredging of a channel. The results may also prove useful for researching the regional sediment budget, and thus optimizing the future dredging activities. Finally, an operator may use auditable monitoring data as evidence that coincidental environmental impact that occurred during his project was not caused by spill from his project.

Summary

Three goals of monitoring can be identified:

- Avoid harm to the environment
- Quantify the side effects of an activity
- Quality control of the intended effects of an activity

For the first of those goals, three parameters may be of interest to measure:

1. Sediment accumulation and erosion
2. Near-bed sediment concentration
3. Water column sediment concentration

Sedimeters can measure #1 and #2. Turbidimeters can measure #2 and #3. It is therefore feasible to formulate the conditions in the permit in terms of these variables, and to require the monitoring of them on a continuous basis, at a certain number of points, in the biotopes of concern.

In the open sea #3 is probably of minor environmental significance, since fishes simply can swim away from the plume (empirical data has demonstrated that they do). The monitoring solution will therefore focus on 1 and 2 only. If #3 is to be explicitly included, it could be done using buoy with turbidimeters at one or more levels in the water.

The sedimeter can also be used for measuring siltation in the navigation channel, as well as for monitoring the erosion of the offshore parts of the beach. It is thus useful for all three monitoring goals.

Part II: Example of a Monitoring Program

After having specified the conditions that must not be exceeded, an environmental permit may task the applicant with providing a monitoring program that ensures compliance, and that can be audited. A draft example of a monitoring program for a beach replenishment project is presented here.

In this example, sand is to be dredged offshore, beyond a coral reef, and transported on barges to the shore. Near the beach there is a coastal inlet with a dredged navigation channel. Table 1 summarizes the objectives of the monitoring program from the project owner's perspective. Since the first point is for internal use only, it is not mentioned in the monitoring plan submitted to the authorities.

To clearly indicate the text of the conceptual plan, it is in Arial font and framed.

Table 1. The goals of monitoring.

Issue	**Question, goal**
Intended benefit	Does it work?
Harm to other stakeholders	To what extent does the project cause siltation in the channel?
Harm to the environment	The biotope must not be harmed by the project!

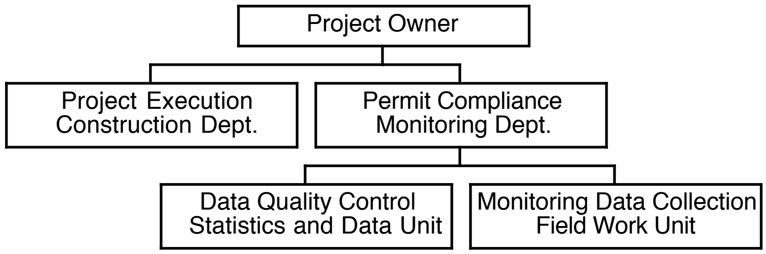
Conceptual Monitoring Plan

The monitoring consists of a network of instrument connected to a computer that calculates geostatistics using kriging, so that a map of the spill is created. Several types of alerts can be generated in response to spill, or to problems with the monitoring system.

Organization

The internal organization is shown in the diagram. The Monitoring Department can order the Construction Department to decrease or cease activities. They also report to the authority agency that supervises permit compliance.

Example of Organization Diagram

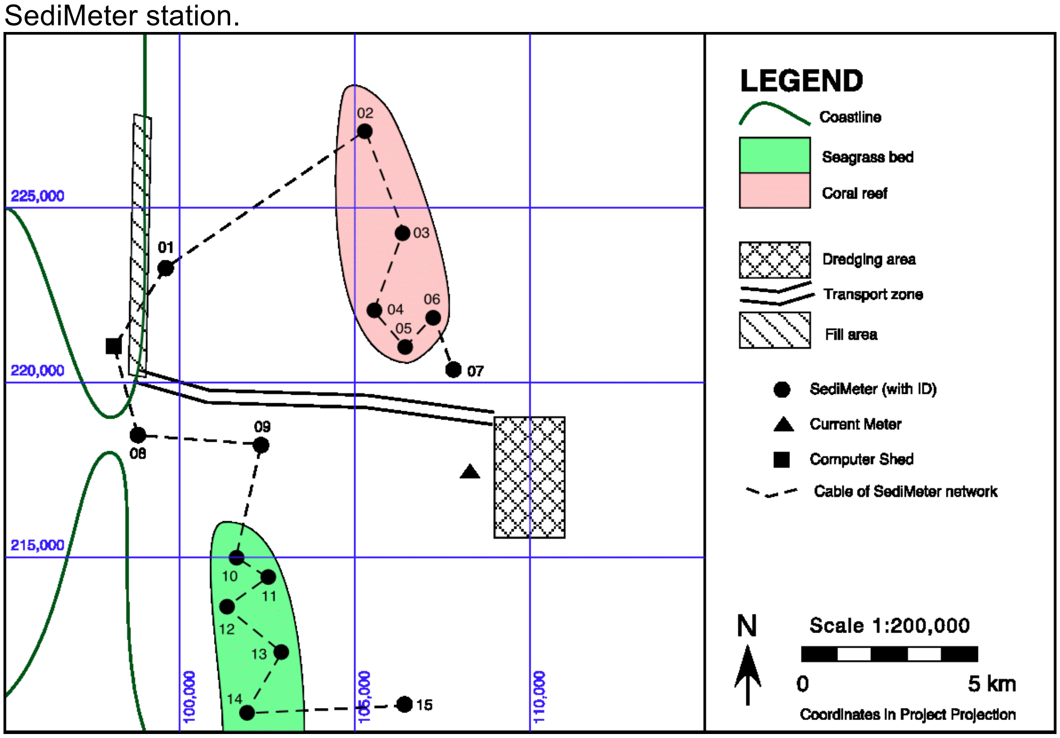


Comment

The monitoring plan should include information on the organizational structure with chain of command, distribution of responsibilities, reporting responsibilities, and the like.

Map

The sediment spill monitoring system consists of fifteen SediMeters in a network (two branches from one central). A computer on land continuously collects data from the stations and makes it available over the internet to the project owner and the supervising authority. A current meter is used to estimate the direction of the spill plume, and the delay between the creation of the spill and its arrival to a SediMeter station.



Comment

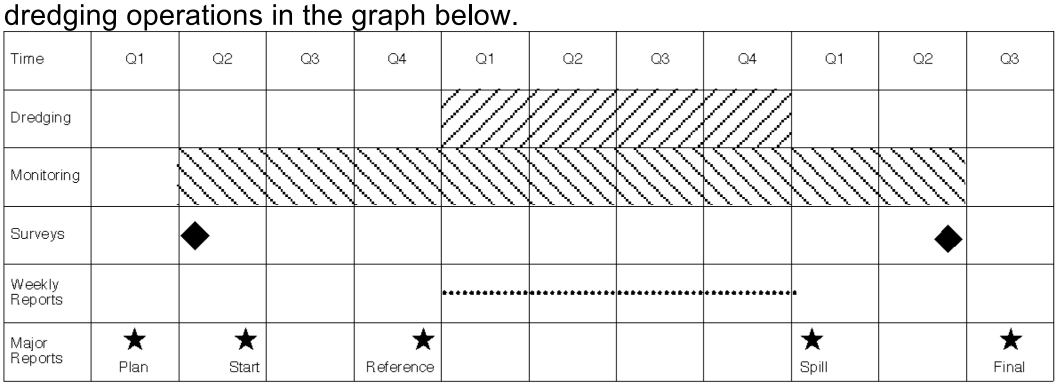
A multi-theme map, as in a geographic information system, may be provided as a spatial overview. The first two themes in the following list are essential, the others are optional:

- the areas of activities (extraction, transportation, deposition, building, etc.),
- the location of monitoring activities (recording sensors, sampling points, etc.)
- any mitigation features (e.g., geotextile barriers, sedimentation zones),
- the bathymetry,
- the geology (rock type on hard bottoms, sediment thickness on soft bottoms),
- the sedimentology (grain size, sediment type),
- the wave climate,
- the currents,
- the sediment transport capacity (preferably for different grain sizes),
- the sessile communities (distribution of key species, or biotopes)
- the oceanography (salinity, temperature, nutrient levels, turbidity, Secchi depth)
- fishing areas
- navigational channels and aids
- administrative boundaries
- protected areas and other specially designated areas

As with all maps, the scale, coordinates, orientation, and a legend, should of course also be provided in a form suitable for the publication media (electronic or paper). The example map is for illustration only, and it is not to scale.

Time Plan

The timing of monitoring, field surveys, and reports are shown in relation to the dredging operations in the graph below.



Starting with the last line, we see that a Plan Report from the project owner to the supervising authority is the first milestone. It details the monitoring plan. Once the authority signs off on it, the monitoring program is started.

Next, the initial survey is undertaken (in this case a bathymetric survey; it can also include estimating biomass, a side-scan sonar survey, etc.). The progress until this point is reported in the Start Report, the most important part of which is of course the survey results.

Shortly before the start of dredging operations the monitoring data is analyzed, and the Reference Report detailing what the normal measurement values are, is issued. It operationalizes the permit conditions into actual numerical values for sediment concentrations and accumulation. After approval by the authority, these values are entered into the computer control system, and the dredging can commence.

During dredging, weekly quality-controlled Data Reports are delivered (in big projects this could be an on-line user interface to a database). All these reports are summarized in the Spill Report after the end of dredging, summarizing how much spill was actually detected.

Some time after the end of dredging, when the monitoring shows that conditions have stabilized, a final survey is made, the monitoring is terminated, and a Final Report issued.

Raw monitoring data can be available on-line with less than a minute delay. These data are, however, not quality controlled. Quality controlled data are available on a weekly basis, such as each Tuesday for the past week (Monday through Sunday).

If an alarm is triggered so that work is stopped, according to criteria operationalized in the Reference Report, an **Incidence Report** shall be issued immediately when the reason has been identified (and submitted to the supervising authority). If the alarm was caused by some data error, the report may authorize the dredging unit to resume work immediately; otherwise it will suggest what changes have to be made to comply with the permit.

Comment

A time schedule of the proposed activities should be included. The relevant phases of the project should be indicated together with the phases of the environmental monitoring.

Furthermore, the reporting schedule should be described (how often and when will there be data updates, status reports, comprehensive reports, final report).

Finally, the section should outline what the milestones are, what criteria are used for evaluating compliance with the permit, and what actions are to be taken in case of failure to comply (either due to a failure of the monitoring program, or if the monitoring program reveals unacceptable side effects).

The permit may either be written so that the supervising authority has to sign off on resuming work, or so that the project owner may authorize himself to restart work once a solution has been found and the authorities have been informed, unless the latter give orders to the contrary within a given period of time (in the order of hours rather than days).

Measurement and Quality Control

All instruments are calibrated or checked prior to deployment. The SediMeters are photographed *in situ* after installation. At regular intervals (depending on local conditions such as depth, light, etc.) the SediMeters are re-visited, photographed, and any impurity is removed with a soft sponge from the optical surfaces.

Data are quality controlled both visually (by plotting them in various graphs), and by statistical methods (such as autocorrelation, filtering, trend analysis, etc.). In recognition of the fact that spurious data can be generated by several random processes, and that the origin of each individual extreme can seldom be determined, statistical outliers are eliminated from the analysis as part of quality control.

Comment

Apart from the quality control on instrument and measurement level, some statistical quality control may be useful for making sure that the distribution of measurement values in time and space conforms to the expected. If it does not the cause should be investigated, as it may indicate faulty equipment, systematic bias, or even improper manipulation of the results. The overlap of the OBS detectors facilitates the quality control.

Analysis

The software presents time-series data from each station (level, trubidity, calculated accumulation and erosion). Option: Krieging between the measurement stations.

Comment

Sediment accumulation and turbidity can not be measured everywhere continuously. The instruments give quasi-continuous data from measurement points. By interpolating between the measured points using kriging, two statistical objectives are achieved at once: An optimal solution is found, and the uncertainty is determined in all parts of the area under study. Thus two maps are generated for each variable, corresponding to the mean and standard deviation, respectively (see Myers, 1997).

Alarms and Contingency Plans

SediMeters in the coral reefs measure the sedimentation and the near-bed sediment concentration. Very limited sediment accumulation is permissible in that biotope, and only very low levels of turbidity (the natural sedimentation rate being in the order of 0.05 mm to 0.5 mm per day). The computer calculates the net accumulation above the reference level. If a sediment accumulation of more than a pre-determined number of mm occurs a red alarm is triggered. Similarly, if the turbidity increases to above the permit value an alarm is triggered. The normal background values to be used as reference will be determined during the pre-dredging phase of the monitoring, and reported in the Reference Report for approval.

The data collection is equipped with an automated alarm system. If a red alarm is triggered the dredging will stop until the cause of the alarm has been determined and it is deemed safe to continue.

The data are also fed into a geostatistical mapping system, so that the uncertainty in between measurement stations can be estimated.

The ***alert levels*** of the system are as follows.

Red Alarm — measured accumulation level at any station exceeds permit, or near-bed turbidity exceeds permit during a predetermined time interval

Orange Alarm — estimated mean **+** std.dev. exceeds permit (essentially an uncertainty alarm indicating insufficient data network)

Yellow Warning — turbidity value exceeds permit in single measurement

Blue Warning —statistically highly improbable pattern that could be due to a measurement error

Green — all systems are fine, normal operation

Comment

If repeated orange alarms are triggered in the same area, the cost of investigating between the measurement stations will rapidly exceed the cost of installing another station to decrease the standard deviation in the siltation estimate. The project owner is thus motivated to seek an optimal balance between station density and cost. The orange alarm, and the requirement of a field survey, thus serves as tools for optimizing the monitoring system station density.

Concluding Comment and Conclusion

This remotely operated network of stations is expected to have significantly lower operating costs than the traditional alternative: ship-based turbidimeter-measurements of spill leaving the work area. The monitoring program may also give cost-benefits to the entire project, by only limiting work in those situations where the spill actually would have a negative effect on the environment.

To fully benefit from these advantages the permit conditions should be formulated in terms of the permissible sediment concentration levels and sediment accumulation, depending on the biotope. The following section deals with these permit condition issues.

Part III: On Permit Conditions and Regulation

Objective

The government body that issues a permit for an activity is also tasked with defining the limits and conditions. In doing so, several potentially conflicting interests must be reconciled. These include:

- The intended benefit of the project
- Keep the harm to the environment at an acceptable level
- Quantify any harm done to other stakeholders and mitigate or compensate
- The beneficiary of the project should bear all costs
- To avoid unnecessary costs, conditions should be as general as possible

The last two points express the notion that the one holding the purse should have as much freedom as possible, within the other constraints, in spending the money. Therefore the rules should preferably be written in terms of the *intended result*, rather than in terms of the methodology to use. This said, for routine projects it is probably cost-effective to use a standard methodology. However, prescribing the methodology in the permit might stifle development. A compromise might therefore be to prescribe the intended result and to recommend, rather than prescribe, the methodology.

Intended Benefit

The concerns of the applicant are of no relevance to the permit *per se*. However, it is advisable to take his need for quality control into account when considering the monitoring program, since the project owner might find the methods that can help evaluating the success of the project, as a side effect, to be more attractive.

Let us consider the case for which the conceptual monitoring program was created. What the permit must consider in this case are the effects on the navigation channel as well as the sea-grass bed and the coral reef.

Other Stakeholders

The effect on the navigation channel can be mitigated (by dredging). The permit may therefore prescribe that the sedimentation in the navigation channel be measured. The permit might for instance specify that the channel bathymetry should be measured before and some time after the end of the project, to assure that no negative effect occurred. In addition, the permit may call for the continuous monitoring of the depth at key points in the channel, for two reasons: to make sure that no adverse effects occur during the project, and to determine the temporal variability of the depth. The latter will help in calculating if a change detected by the bathymetric survey is significant or not. The purpose is thus mainly to quantify changes, as a basis for mitigation or compensation.

Data Collection

Choosing Measurement Parameter

Permit conditions should ideally be formulated so it is possible to create a cost-effective monitoring system that can issue a real-time alarm if conditions are exceeded. As an example, sediment accumulation can be detected with a sedimeter. SediMeter™ model SM3 is capable of detecting 0.1 mm of sediment accumulation, which is less than the lethal level for the majority or all of benthic fauna.

The sedimeter can be used to detect temporary deposition, such as sedimentation of spill during slack tide, which is hours later washed away by the flood or ebb current. A deposition of a mud blanket will typically be distinguishable from the solid bottom in the data, since clastic sand, mangrove mud, coralline material, etc, have different albedos in the IR region.

Uncertainty in a Point

Regardless of what instrument is used, one must consider the interpolation and inherent uncertainties. The interpolation is both spatial and temporal. Disregarding instrument uncertainties, the first uncertainty relates to if the measurement really is representative for the point and time where it was taken.

The heterogeneity of the signal may be significant at low levels. For instance, seaweed or plankton floating by the sensor could give strong signals (this is similar to the "nugget effect" in geostatistics). Geostatistical analyses show that the uncertainty is best decreased by taking a number of samples at each measurement station, in close proximity to each other, so one can estimate the local variability (Myers, 1977).

The sedimeter with its 36 overlapping backscatter detectors (+1 in the 3rd generation) provides many near-bed turbidity measurements, which makes it possible both to improve precision by averaging, and to estimate the magnitude of the nugget effect. As the bottom moves up or down, a different subset of detectors may be averaged, so one always stays at the same level above the bottom.

Pollution Limits

Absolute Pollution Limits

It seems ideal that the acceptable level of pollution should be determined for each species and each biotope, and that the permit should be formulated in terms of not exceeding those levels. Suppose that biotope X is found to tolerate only up to 10 mm of sediment accumulation. The permit could then say, "if a sediment accumulation of 10 mm is detected the work should stop immediately." The uncertainty inherent in all measurements must of course be allowed for in the criterion. However, in some cases the biotope's tolerance may not be known in absolute terms.

Relative Pollution Limits

A practical workaround is then to allow only a limited change compared to the normal conditions, e.g., an increase by max 50% or the detection level of the instrument, whichever is larger. In practice, the applicant must measure the normal conditions during a time period before the project, evaluate what the normal conditions are through statistical methods, and then keep measuring during the execution phase using the exact same stations and methods.

The permit can be formulated in terms of the statistical parameters of the reference period, for instance, "the sediment concentration 10 cm above the bottom must not exceed the reference by more than 10% in average during any period of active dredging, and it must never exceed the 99 percentile in the reference data by more than 50% over a 5-minute period."

The accumulation of sediment in an area can be restricted by a similar condition. If no sign of accumulation was found in the reference period, ten times the resolution of the instrument can be used as a limit: "Work must be stopped immediately and an investigation launched if a sediment accumulation of 10 mm or more is indicated in an area designated as sensitive, if no accumulation was detected there in the control period."

As regards the normal, one may either use a single value such as the mean, the median, or the 90-percentile, or use the entire cumulative distribution curve. To avoid postponing judgment of permit compliance until after the end of the project, when it is too late to remedy any harm done, this cumulative curve could be calculated on a monthly, weekly, or perhaps even daily basis instead.

Interpolating Between Measurement Points

Spatial Uncertainty

In the previous sections absolute and relative pollution limits were discussed, but only in the measurement point itself. One must also address the spatial uncertainty that stems from interpolating between measurement points.

In kriging, the map has the study area divided in square cells. If just one large cell is produced, it is equivalent to calculating the mean and standard deviation of all data using traditional statistics. However, the pollution might be much larger within a small part of this super-cell. On the other hand, the more and smaller the cells are, the larger is the uncertainty in each cell.

When evaluating the permit application it may not be clear what the area extent of the spill plume will be. If this is the case, a number of cells must be used, so that the direction and range of the spill plume influence can be determined. As mentioned, the trade-off is that the uncertainty increases. However, the uncertainty is not homogenous, but varies with the distance to the measurement points. The rate of this variation is expressed by the variogram, which is related to the spatial correlation. The uncertainty thus depends both on the distance between measurement points, and on uncertainties at each measurement point (including the geostatistical so-called nugget effect, and instrument limitations). All of these can be estimated.

Permit Strategy alt A: Specifying Confidence Level

The authorities in charge of permitting have a choice of how to formulate the permit (this may also be done on the legislative level in some jurisdictions). The main choice is whether to specify the confidence level of the result, or the method to use.

Using sediment accumulation as an example, the permit can specify the confidence level in the following terms:

The accumulation must not exceed* X *mm at the* Y *% confidence level within any* Z *m^2 area during any* Q *hour period.

Or for sediment concentration in relative terms:

The near-bed sediment concentration must not exceed* X *% above the normal at the* Y *% confidence level within any* Z *m^2 area during any* Q *day period.

By specifying the confidence level, both the temporal and spatial uncertainties must be taken into account. Such a condition forces the project owner to ensure a large resolution and precision in the measurements in the areas where spill occurs, while allowing a lower measurement density farther away.

In this situation, all the details about how many measurement stations to use and where to locate them can be left for the project owner to figure out, as long as he measures the correct parameter with the appropriate precision. The size of the cells (Z) dictates the spatial resolution of the kriging, the confidence level (Y) controls the number and location of measurement stations, and the instrument precision, while Y and Q together control sampling rate.

Permit Strategy alt B: Specifying Methodology

As a contrast, another strategy would be that the permit specifies how many measurement points there should be, and the location of them. It is readily seen that this puts the authorities in the position of designing a working monitoring program. Thus, any accuracy problem can be blamed on the authorities' design, why they will only be able to enforce the technical execution of the permit; if the monitoring design turns out not to work, there is nothing anybody legally can do to fix it. (In practice the project owner may cooperate voluntarily to maintain good relations, especially if he depends on it for future business.)

Recommendations

Specifying well-formulated conditions (i.e., precisely targeted and cost effective) does require rather detailed knowledge about the sensitivity of the biotopes and species. Due to the cost benefits later, *such research would appear to be a good investment* for society as a whole. The more science knows about the sensitivities of organisms and biotopes, in time as well as in space, the more cost-effective the permit—and thus the monitoring—can be made. It can be seen, however, that *relative limits can provide a workaround if absolute limits are unavailable*.

Fulfilling geostatistical permit conditions requires the extensive use of statistical methods in both the planning and execution of the monitoring. However, *the methods lend themselves to being standardized in the form of computer software*. In order to assure that the methods are verifiable the tools must be transparent, which means that it may be necessary to either require the use of open source software, or to require (for auditing purposes) intermediate data between each step if calculations are made using commercial software.

It remains to be determined what confidence level is reasonable, and in what combination of spatial and temporal resolution. The interpolated uncertainty is the main unknown. The use of different variograms in different directions, and of other, correlated, parameters in a process known as co-kriging, can perhaps increase the precision. At any rate, *practical tests followed by statistical calculations should be made* to arrive at reasonable and realistic permit conditions. The project could be executed as a data collection effort before, during, and perhaps after a dredging operation, followed by data analysis. Data will likely prove useful also for other researchers (marine biologists, sedimentologists, oceanographers), and for the development of open-source software.

Contrast: Ship-Based Turbidimeter Measurements

The solution outlined in this paper can be contrasted with the probably largest spill monitoring effort so far, during the building of the Øresund connection between Sweden and Denmark. The present strategy was created in response to the extreme costs of that solution.

The permission stipulated that spill from the dredging of 7.5 million m^3 (9.8 million cubic yards) be limited to 5%. This was then made operational by defining that spill was the sediment that left the work area (or barges) in suspension, where the work area was defined as the dredging zone plus 200 meters on all sides. This suspended sediment transport was measured by an array of turbidimeters towed after a ship, and a Doppler current meter. The ship cruised day and night along the 200-m line, measuring how much sediment went into, and out of, the work area (actually several identical ships were used to allow for crew change and rest). To comply with the Danish permit, the mussel banks were in addition regularly inspected by high-frequency side-scan sonar to detect possible sediment accumulation.

This monitoring program was of course very expensive to operate. Furthermore, it did not directly measure parameters that really matter for the biota. Instead it measured the suspended sediment concentration, from which sediment flux was calculated, so that the sediment spill could be determined as a percentage for the whole project (which lasted for several years). The condition in the Swedish permit was very simple (5% measured to within ±20%), but measuring it was not, and it had little direct bearing on the environment.

Legal and Administrative Differences

As regards the permitting procedure this project provided interesting insights. The project ran across an international border why two countries with different systems were involved. The process can be compared as follows, after a decision to build a bridge was agreed to by the Danish and Swedish cabinets.

Step	Denmark	Sweden
Legal permit	The parliament passed a Bridge Law presented by the cabinet	The bridge consortium applied for a permit at the Water Court
Environmental conditions	Part of the Bridge Law	Decided by the Water Court to operationalize the cabinet's condition of zero-impact
Opposing interests	Handled in the Bridge Law	The Water Court can order monitoring and, based on the results, order the applicant to pay compensation many years later
Environmental monitoring	Carried out by the project owner	Carried out by the project owner
Supervision of the permit	By the environmental protection agency	By the central government's regional office (and their EPA department)
Authority	The minister can intervene and stop the work 'immediately	If the authorities and the project owner do not agree the court must settle the dispute

In Denmark the executive branch handles the process, and it has the full power of the executive at its disposal. In Sweden the judicial branch is balancing the interests of the various parties (all stakeholders may argue before the court and their legal costs are covered by the applicant), while the executive is limited to somewhat of a clerical role. There is also a government board whose role it is to argue the case of Mother Nature in the court. The Swedish Water Court, established in 1919, was in 1999 replaced by the Environmental Court, and its responsibility was expanded to all issues of changes to nature.

The Danish method of creating a specific law, and of the minister intervening, are both illegal in Sweden. Since 1809 the Swedish Constitution says that no elected official can intervene in—or even have a stated opinion about—a specific case, and no law can be created for a specific purpose, but all laws must be of a general nature. This is considered to give more legal security for individuals and corporations, and it certainly shields politicians from the temptation of corruption. Most countries do have ministerial rule, though, and in some jurisdictions the laws themselves may be so specific as to actually specify measurement methods, directly or indirectly.

These comparisons show that the permit process and supervision can be arranged in different ways according to the administrative traditions of each country, where each has its pros and cons.

Conclusions

- Siltation can be monitored in a biotope by *sedimeters, in combination with geostatistical methods* for interpolation and uncertainty determination (where mid-water turbidity needs to be limited, mid-water turbidimeters can be used also)
- The system can be networked so that alarms can be issued in case of permit violations.
- A sedimeter monitoring system can also measure erosion off the beach, sedimentation in navigation channels, wake-induced re-suspension on mud banks, etc.
- Pollution limits can be expressed in absolute or relative terms, where the latter can be used in a permit even absent detailed knowledge on the sensitivity of an ecosystem.
- An applicable permit must specify four values: X - the pollution threshold value, Y - at what confidence level the threshold value is defined, Z - at what spatial resolution the threshold value is defined, Q - at what temporal resolution the threshold value is defined. It is recommended to also specify minimum sensor resolution.
- Suitable values for X, Y, Z, and Q should be determined based on actual field data.

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